

# Crossing Vortex Lattices in Layered Superconductors

## Scientific Achievement

In very anisotropic layered superconductors (such as  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$  (BSCCO)) a magnetic field tilted with respect to the c-axis typically creates a composite lattice consisting of two sublattices: sublattice of pancake-vortex (PV) stacks generated by the c-axis field component and a sublattice of Josephson vortices (JVs) generated by the in-plane field component (crossing lattices). The interplay between different energy and length scales, which can be tuned by the magnitude and orientation of the magnetic field, leads to a very rich spectrum of static and dynamic properties of this composite vortex lattice.

We theoretically investigated the structure of an isolated JV inside a pancake lattice. We found that the JV transforms into a solitonlike topological defect with decreasing anisotropy. At small c-axis fields PVs form chains along the JVs allowing the experimental visualization of their structures. We theoretically investigated structure of an isolated vortex chain for different anisotropies and field components and found a very rich spectrum of possible states and several phase transition between them. We have explored the pancake-flux configurations in tilted fields in pristine and artificially patterned BSCCO crystals using a magneto-optical technique. We found that PVs enter the sample along the JV stacks and move in unison with them. We demonstrated the possibility to control and manipulate these pancake flux using JVs in combination with artificial gates at the edges and sculptured patterns at the top surfaces of the crystals produced by Focused Ion Beam (FIB) writing.

## Significance

The discovery of new types of vortex lattices in superconductors and understanding their properties has a high basic-science value. We significantly advanced our theoretical understanding of the crossing-lattices states in the different regions of fields and tilt angles. These results have been presented in numerous International conferences. The crossing-lattices state has several properties which can be utilized for applications. Significant interaction between sublattices allows one to use one sublattice (JVs) to manipulate other sublattice (PVs). In combination with artificially fabricated microstructures, this gives attractive possibility to deliver individual PV stack to desired location and prepare designed flux structures.

## Performers

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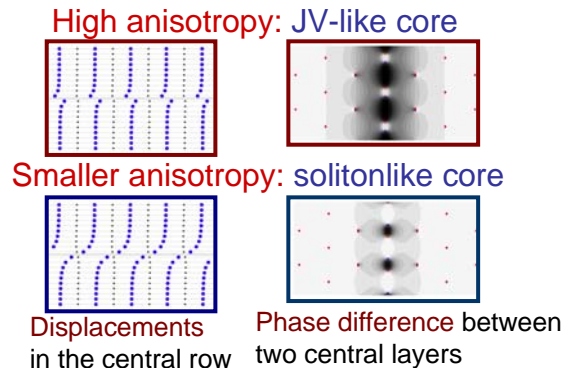
## Recent achievements

- **Theory**
  - Josephson vortex inside pancake-vortex lattice
  - Vortex chain structure
- **Experiment**
  - Imaging Josephson vortices using pancake stacks

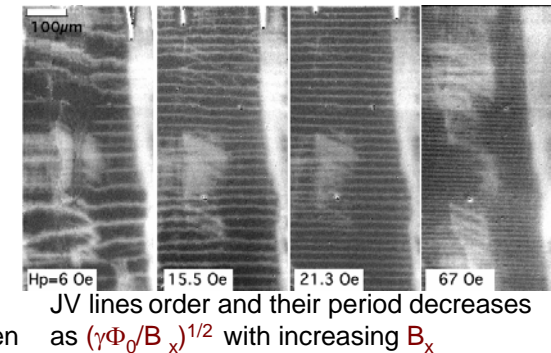
## Future directions

- **Theory**
  - Phase diagram at moderate anisotropies
- **Experiment**
  - Manipulate pancake-vortex flux with Josephson vortices

Core of an **in-plane vortex** inside dense pancake vortex lattice



Evolution of the **JV lattice** with increase of in-plane fields,  $H_z=2\text{Oe}$  (MO images)



## Vortex-Chain Structure

Vortex chains are formed at small c-axis fields  $B_z=0.1 - 3\text{ G}$ . The chain structure evolves from **crossing chain** at high anisotropy to **tilted chain** at small anisotropy via nontrivial **intermediate states**.

High anisotropy: **Crossing Chains**



Smaller anisotropy: **Tilted Chains**

